The Challenge of Evolving Mission Operations Tools for Manned Space Flight

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Abstract

In this paper we describe the impact of changing mission operations requirements on mission planning tools for human spaceflight. We use the task of planning S-Band communications for the International Space Station (ISS), as a case study. Existing planners such as the Consolidated Planning System (CPS) permit the declaration of requirements for activities, such as the set of allowed S-Band communication modes, as well as temporal constraints between activities. CPS allows operators to add activities, delete activities, and automatically generate plans; however, it is a large, monolithic system and requires significant expertise to operate. The On-board Short Term Plan Viewer (OSTPV) is suitable for viewing Short Term Plans (STPs), of roughly a week's duration, generated with CPS, and allows users to make limited changes to plans. It is used by operators in Mission Control in the United States and Europe, and onboard the ISS. However, OSTPV does not include the capability to check STPs after modification against the constraints used to generate the original plan. Operational and technical constraints preclude using CPS to support modifications to the STP. However, recent changes to ISS operations have increased the need for modifying plans within days of plan execution, and have complicated the task of ensuring those plans meet all relevant constraints. As a result, we have developed a new tool suite to check the STP after editing, and to mark up the plan so that problems can be easily detected using OSTPV. This suite is derived from the Extensible Universal Remote Operations Planning Architecture (EUROPA), a toolbox developed at NASA Ames Research Center, and previously used to develop mission operations tools for Mars missions. We will describe these tools, discuss the operations concepts and existing tools that drive this new tool development, and discuss the future evolution of this technology.

1. International Space Station Mission Operations

In this section we provide an overview of ISS operations. For more detailed overviews of this task and for insight into some of the organizational and cultural challenges, the reader is referred to [1] and [2].

ISS Planning is the complex tasks of prioritizing, negotiating, and finalizing crew activities for a given amount of time. Planning work begins when NASA's Program Office issues a Program Document for an increment, an ISS mission timeframe that usually lasts six months.

Various planning activities are done to create seven main "planning products" – some of which will be discussed in detail later in the paper. Planning activities at JSC are divided into long-term and short-term timeframes. Long-term planners are responsible for plans that are three weeks or further out, and deal mainly with negotiating crew time and constraint management. Short-term planners sit on console and deal with all real-time and next-day planning issues. Plans transition from long-term to short-term at three weeks out and are transferred from one planning system to another at one week out. Other NASA Centers and International Partners (IPs) have their own tools to do ISS planning work partly due to politics and budgets, but also because JSC's tools do not meet everyone's needs.

For the purposes of this paper we focus on a subset of the planning process covering the following staff positions:

• ISS Planning Group Leads (all three locations): Group leads manage and coordinate the work efforts and tool development initiatives of both the long-range and realtime planners at each of their respective locations.

• Operations Planners (Ops Planners) at JSC: Ops Planners are long-range planners, and are tasked with establishing the initial time line for the increment. Their work begins 9 months in advance. Activities include gathering requirements for the mission, planning the activities into the mission increment and refining plans until they are execution-ready (5 days-out from execution). JSC Ops Planners are also the master integrators of the various plans generated by MSFC and Russia.

• Real-Time Planning Engineers (RPE) at JSC: RPEs sit on-console making real-time changes to plans that are 0- 5 days out. Most typically, the RPE that sits on-console in the "front-room" (Mission Control Center) concentrates on altering the plan that is currently being executed. While the RPE, serving the "back-room" of on-console alters plans 1-3 days out that are prompted by real-time changes to the current plan being executed.

2. Current Mission Operations Tools

Currently, the Long-Range Plan (LRP) is generated for roughly 6 months worth of ISS activities (equal to one ISS Increment and crew rotation). Once the major mission milestones are decided, the LRP for the Increment is generated using the Consolidated Planning System (CPS). CPS is the principal tool used by the Operational Planners. CPS permits the declaration of requirements for activities, such as the set of allowed S-Band modes, as well as temporal constraints between activities. CPS allows operators to add activities, delete activities, and automatically generate plans; however, it is a large, monolithic system and requires significant expertise to operate. For this reason, a Short-term Plan (STP) is exported from the LRP, (in the CPS system) and loaded into a light-weight web based timeline viewing tool called the On-board Short Term Plan Viewer (OSTPV).

OSTPV (Figure 1) provides an intuitive interface to view the current STP. It provides a Gantt-chart like view of the plan, with bands representing pertinent information concerning ISS orbit, communications asset coverage, and activities performed by each crew member. Tool-tips allow access to a variety of related notes that further elaborate on the activity. In addition to these features, the tool allows adding and removing activities from the STP as well as changing the times of a subset of the scheduled activities. Real-time Planning Engineers (RPEs), both in the United States and International, as well as astronauts onboard ISS, can examine the STP this tool; onboard, crew use OSTPV via the Personal Computing Systems called SSCs (Space Station Computers).

Once approved, the Short Term Plan (STP) is converted into the OSTPV plan one week out from the date of plan execution. The timeline data from CPS is exported into OSTPV without all the constraint

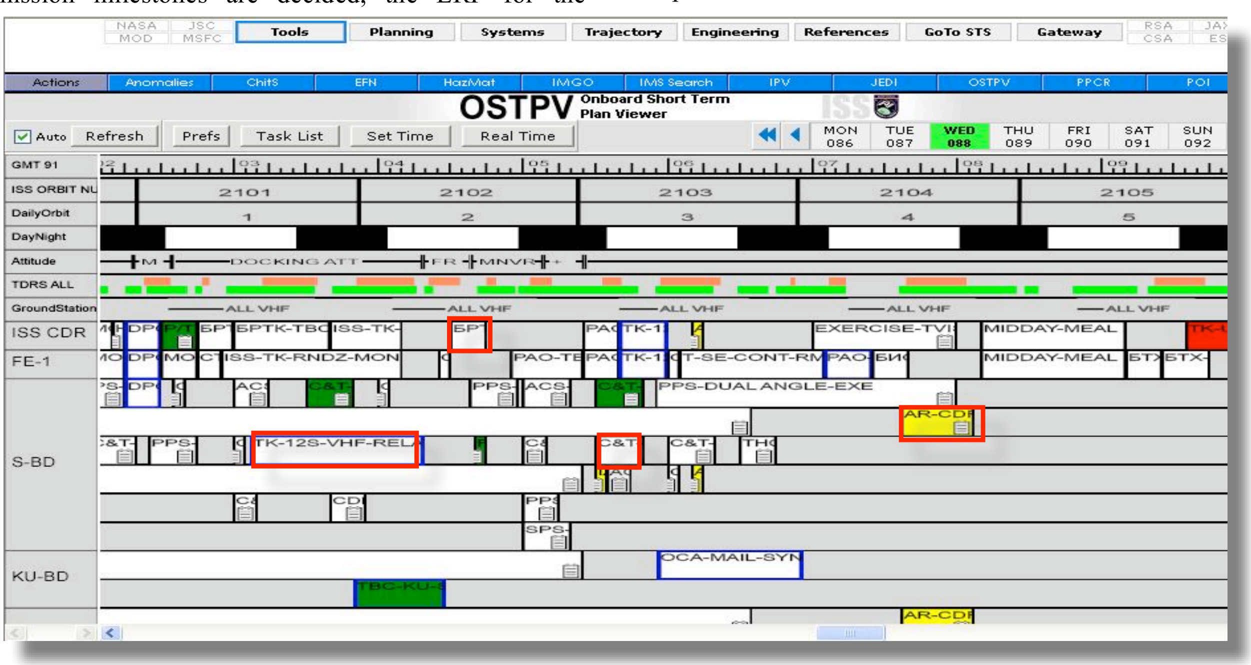

Figure 1. On-board short term plan viewer interface.

modeling, activity dependencies, and procedural instructions. JSC generates STP Notes to fill in the information gaps. STP Notes is a Microsoft Word document that outlines any special instructions or procedural steps associated with an ISS activity. JSC generates STP Notes from the procedural data included in the CPS-formatted STP plan. Any activity deviations from the master plan are recorded in the STP Notes.

OSTPV also provides limited ability to modify plans, either by adding late-breaking activities or by moving activities. With the advent of S-Band requirements, moving activities may lead to violated S-Band constraint violations that cannot be easily checked within OSTPV. Furthermore, late-breaking activities that force changes in the S-Band plan may require extensive replanning that also cannot be supported by OSTPV.

Changes to the plan are requested via a Planning Product Change Request (PPCR). It takes three individuals to approve the PPCR before any changes are made. Once the request is approved, changes must be made to both CPS and OSTPV systems as they are not linked. At the same time, any changes made at JSC must be manually made at MSFC and the IPs.

The need for intense manual reviews is increased as the plan transitions from CPS into OSTPV because constraint models that were embedded in the CPS plan are stripped of the file. This requires the Lead Real-time Planning Engineer (RPE) to inherently know the constraint models so that she/he may act quickly in a real-time, re-plan situation and for more iterative manual reviews to be conducted by the execution team (flight controllers, experts and specialists).

3. Evolving Needs, Revising Plans

The first human crew occupied the International Space Station (ISS) in 2000. Since then, ISS has been continuously occupied, and undergoing sustained development. Evolving operations needs have led to changes in ISS operations software. In order to respond to this need, NASA Ames Research Center and NASA Johnson Space Center have engaged in a sustained effort to develop new mission operations tools. An overview of these efforts is provided in [6]. Among these efforts is the need for improved capability of the RPEs to determine when proposed changes to the daily plan may violate constraints. In particular, the addition of new solar arrays installed on Flights 13 and 10.A in 2007 along with the impending installation of new lab modules from both JAXA (Japanese Space Agency) and ESA (European Space Agency), required extending the S-Band telemetry format to capture all necessary data. In response to this need, activities on ISS are constrained to use different S-Band formats in order to ensure the needed telemetry can be sent to ground. Only one S-Band mode may be active at any time, but any number of activities may execute concurrently as long as they are allowed to use the active mode. While changing modes is essentially instantaneous, a Swap activity of fifteen minutes' duration must be scheduled to implement the changeover at the designated time. **(Add more specifics here; specifics of packet format and telemetry downlinked, frequency of PPCRs, PHALCON's need to run procedures with unpredictable S-band needs in partiucular.)**

This new mode of operations imposes added complexity on management of the STP. An activity occurring during an interval of time constrains the S-Band mode at that time. The set of S-Band modes employed over time (i.e. the S-Band plan) may be updated, requiring validation of the new S-Band mode plan against the rest of the STP. Furthermore, activities may be able to use several possible S-Band modes. Thus, new activities may only be added at times such that a compatible S-Band mode is used in the current S-Band plan. Also, problems that arise can be fixed by either changing the time of activities or by changing the S-Band mode the activity uses. Activity S-Band requirements are collected using a tool called LISA; however, S-Band requirements are added to CPS by hand. As previously stated, the S-Band requirements are not exported to OSTPV plans. Thus, it is possible to change the plan and violate the rules without knowing it. Finally, there is a desire to minimize the number of times each week that packet formats are swapped, which introduces complexity into the scheduling of activities.

We now describe the way the S-Band constraints are captured by CPS, how the CPS plans are exported for use by OSTPV, and how difficult it can be to find problems with S-Band constraints after changes are made to the STP. At present there are 9 S-Band modes, described by 3-letter codes; the modes are JJJ, JJK, JJL…JLL. For each individual activity in the STP, CPS has a set of rules that govern how it must be scheduled. This amounts to a set of legal S-Band modes that may be used while the activity is executing[1]. The S-Band mode rules are captured in one or more rules that enumerate the set of legal S-Band modes. Due to the limitations on the rules language, the modes are represented in CPS as the integers from 1-9; mode JJJ is represented as 1, mode JJK as 2, and so on. CPS supports an AND-OR tree syntax for rules; a disjunction of rules is in order to capture the complete set of modes (shown in Figure 2).

In the OSTPV representation of the STP, activity descriptions include references to S-Band modes employed, if applicable; however, these references use the three-letter code (Figure 4). There is no automated translation from OSTPV's format to the CPS format. Thus, if the OSTPV plan is changed, the RPEs must know the mapping from the three-letter codes to CPS's numbering scheme, as well as where to enter the changes in the CPS rule base, in order to ensure consistency. Furthermore, the CPS field used to denote the S-Band mode is a range of the integers from 1-9, with the smaller value specified by the field ACTV_COND_RANGE_MIN_TIME , and the larger value specified by the field ACTV_COND_RANGE_MAX_TIME (Figure 2). These fields are easily confused with activity time parameter names, leading to further potential for error.

There is a further complication involving correlating activity rules in CPS and activity descriptions in OSTPV. The tools use different schemes to enforce unique identifiers amongst activities. The CPS rule base includes a relational table correlating the OSTPV and CPS activity identifiers (Figures 2 and 4), but it is difficult for RPEs to chase down the correct activity in the CPS rule base. Worse yet, the relation is implicit, and the parameter names used in the two schema increase the chances for confusion; the CPS schema's parameter is named the OSTPV-ID, and the OSTPV schema's parameter is named the CPS-ID. On rare occasions, the OSTPV identifier may be re-used when two CPS users create an OSTPV-readable version of the STP, which further complicates the issue. Finally, if a new activity is added to the STP in OSTPV, it is impossible to associate it with an activity added to CPS.

4. Deep Space Mission Operations Tools

EUROPA is a constraint-based planning framework developed at NASA Ames Research Center [4].

[1] CPS generally allows arbitrary temporal constraints on its conditions; however, usually the S-Band mode starts when the activity starts, and ends when the activity ends.

```
<ACTIVITY>
<ROW>
<TML_NAME>SPICER_PKTSWP_AMES</TML_NAME>
<ACTV_ID> A000000005B51E3JSCP0</ACTV_ID>
<ACTV_NAME>IFM-LAB1S6 MECH-T/S</ACTV_NAME>
<ACTV_OSTP_ID> 3 </ACTV_OSTP_ID>
…
</ROW>
</ACTIVITY>

<ACTIVITY_CONDITION>
<ROW>
<TML_NAME>SPICER_PKTSWP_AMES</TML_NAME>
<ACTV_ID>A000000005B51E3JSCP0</ACTV_ID>
<ACTV_COND_RELATION_CODE>
</ACTV_COND_RELATION_CODE>
 …
<ACTV_COND_START_TIME>
0
</ACTV_COND_START_TIME>
<ACTV_COND_END_TIME>
1800
</ACTV_COND_END_TIME>
<ACTV_COND_RANGE_MIN_TIME>
2
</ACTV_COND_RANGE_MIN_TIME>
 <ACTV_COND_RANGE_MAX_TIME>
3
</ACTV_COND_RANGE_MAX_TIME>
</ROW>
<ROW>
<TML_NAME>SPICER_PKTSWP_AMES</TML_NAME>
<ACTV_ID>A000000005B51E3JSCP0</ACTV_ID>
<ACTV_COND_RELATION_CODE>
O
</ACTV_COND_RELATION_CODE>
…
<ACTV_COND_START_TIME>
0
</ACTV_COND_START_TIME>
<ACTV_COND_END_TIME>
1800
</ACTV_COND_END_TIME>
<ACTV_COND_RANGE_MIN_TIME>
5
</ACTV_COND_RANGE_MIN_TIME>
<ACTV_COND_RANGE_MAX_TIME>
5
</ACTV_COND_RANGE_MAX_TIME>
 </ROW>
…
</ACTIVITY_CONDITION>
```

Figure 2. Fragment of a CPS specification of an activity and S-Band mode rules. The rule shows the fields containing the OSTPV activity identifier, and the S-Band modes specified as a disjunction of 2 ranges of the numerical values from 1-9.

EUROPA was a component of the MAPGEN activity planning tool for the Mars Exploration Rovers [5]. EUROPA2 is the next generation planning framework also developed at NASA Ames. This framework has been integrated with Ensemble, a specialization of the publicly available Eclipse framework developed by IBM. Mission operations tools built from Ensemble components have been baselined for both the upcoming Phoenix and MSL Mars missions. An overview of the evolution of this technology is provided in [3].

One of the primary lessons both of direct MER feedback and Human Computer Interaction (HCI) studies was that the planning system for Phoenix and MSL must have a far more mixed-initiative flavor than it was possible to deploy on MER. When creating or modifying a plan, the user must have almost complete control over where activities are placed on a timeline. It can be very disconcerting for activities to jump around for an apparently unknown reason, even if it is to correct a temporal or flight rule violation. It is therefore important that the user know why a particular action is taken place. In addition, users must be able to ignore changes the planning system would like to make to the plan based upon its model, as during the time critical operational process, operating rules may be modified or relaxed for special circumstances or model bugs may be found.

In the case of the current design, the user is essentially given complete control and uses the planner as an advisor. As the user manipulates the plan, the system is automatically communicating with the EUROPA planner behind the scenes, determining if there are temporal violations. The planner is always acting in either a passive, informational way or acting at the direct request of the user in a way that can be easily undone. It will alert the user to a violation without acting upon it unless explicitly told to do so by the user. The planner does not create user level activities or constraints on its own. It will suggest such actions to the user in appropriate situations but then relies on the client to manipulate the plan according to those suggestions at the user's discretion.

5. New Mission Operations Tools

The emphasis of the EUROPA technology on reporting constraint violation made it a candidate for augmentation of OSTPV. In this instance, the RPEs need centered on the ability to check for and report violations of S-Band requirements efficiently, without reliance on the time-intensive process of consulting CPS. The task was to write the rules in CPS in the rules language to EUROPA, then analyze the OSTPV plan in order to check for violations of the S-Band conditions.

While the rules languages of CPS and EUROPA are similar, there are some important differences. The critical difference is that in CPS, each activity instance has a set of rules associated with it, while in EUROPA, each activity class has a set of rules that apply to every instance of the activity. This difference worked to our advantage; we wrote a set of EUROPA rules applying to a generic activity that uses the S-Band communication system. These rules do not restrict the set of legitimate S-Band modes. We then analyze the CPS rule base to identify each CPS activity that both uses the S-Band communication system, and has an OSTPV identifier. The set of allowed S-Band modes can be added to the plan as constraints on activity instances. With this information, we can then analyze the OSTPV plan to determine the exact time each activity is scheduled, and which S-Band mode the activity uses, along with the S-Band plan that indicates which modes are active at which times. The assembled plan is then analyzed in order to detect conflicts that may arise as a result of plan modifications.

The specification language for EUROPA was originally designed to support the search for feasible plans, rather than the search for violations. However, the new version of EUROPA used to support Phoenix and MSL incorporates a combination of specialized rules and post-processing software to detect rule violations. The general modeling technique is also described in [7]; in this paper we describe the specific instantiation used to handle the S-Band case.

For each condition (in this case the 9 S-Band modes) we introduce a multi-capacity resource R_i $i=\{1..9\}$. Each resource has maximum capacity M; M can be any large number but must be much larger than the number of activities that could execute concurrently and use the same S-Band mode. Denote the available resource of R_i at t by $A(R_i,t)$. We initially have $A(R_i,0)=0$. The S-Band plan consists of a sequence of modes I, each of which holds over an interval [a,b] (Figure 4). Note that S-Band mode I in the S-Band plan is isomorphic to the index i of each resource in the model. The EUROPA rule set contains the following rule: if mode I appears in the S-Band plan, then add M to R_i's availability over the interval [a,b]. For each activity A that uses the S-Band in the schedule, we add the following rule to the EUROPA rule set: if A uses mode i in the interval [x,y] then subtract 1 from R_i's availability over the interval [x,y]. We introduce another resource (denoted 0 for consistency with the notation of the S-Band modes) to handle swaps, which has capacity M and initial availability 0. The relevant rules is: if a swap S occurs in the plan over the interval [x,y] then add M to R_0's availability over the interval [x,y]; if mode I

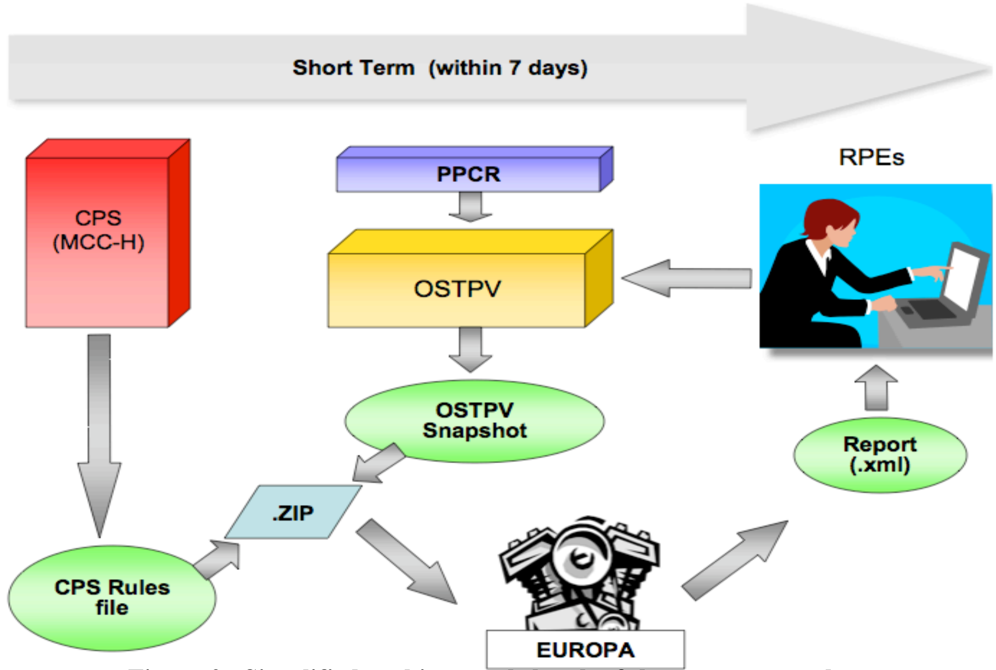

Figure 3. Simplified architectural sketch of the prototype tool to check STPs after modification in response to a PPCR.

appears in the S-Band plan, then subtract 1 from R_0's availability over the interval [a-15,a]. For all resources, a rule is violated at time t if $A(R_i,t) < 0$.


```
<Activity>
   <id>7e3719f1-8e63-45db-93be-e1becb3b8d20</id>
   <Name> IFM-LAB1S6 MECH-T/S </Name>
   <StartTime>2006-11-06T10:45:00</StartTime>
   <EndTime>2006-11-06T14:45:00</EndTime>
   <Duration>240</Duration>
   <CpsId>3</CpsId>
  …
<\Activity>

<ConditionBandScheduledInstance>
   <id>b555807b-fc51-4449-9ffc-a9b9e0032829</id>
   <ConditionBandDetailId>
    b4fdd848-d7da-46a8-b895-79467e7cfd39
   </ConditionBandDetailId>
   <StartTime>2006-11-06T08:30:00</StartTime>
   <EndTime>2006-11-06T14:00:00</EndTime>
   <Label>JJK</Label>
 </ConditionBandScheduledInstance>
<ConditionBandScheduledInstance>
   <id>b555807b-fc51-4449-9ffc-a9b9e0032829</id>
   <ConditionBandDetailId>
   b4fdd848-d7da-46a8-b895-79467e7cfd39
   </ConditionBandDetailId>
   <StartTime>2006-11-06T14:00:00</StartTime>
   <EndTime>2006-11-06T18:00:00</EndTime>
   <Label>JKK</Label>
 </ConditionBandScheduledInstance>
…
```


Figure 4. Fragment of the plan exported to OSTPV from CPS. An activity using the S-Band is shown to hilight the different field describing the activity identifier, and part of the S-Band plan is shown to hilight the different fields and contents used to describe the S-Band modes.

In order to identify activities leading to violations from times t at which $A(R_i,t) < 0$, we introduce the notion of transactions, in order to repeat the description used in [7]. A transaction is a time and an impact on a resource, either adding to its availability or subtracting from its availability. We first define a "raw culprit" to be any consumer (negative) transaction that precedes the time of the violation. Next we delete any raw culprits that are "cancelled" by some subsequent producer (positive) transaction of equal or larger size that also precedes the violation. The final culprit transaction set is given as those remaining after the cancellations. A separate procedure traces the transactions back to the top-level activities that produced them.

We motivate this by an example (Figure 5). The S-Band plan contains one interval in which the S-Band mode is set to JJJ, and a subsequent interval in which the S-Band mode is set to JJK. There are two overlapping activities using mode JJJ, both of which are wholly contained in the first interval of the S-Band plan. There is one activity using mode JJK that is wholly contained in the second interval of the S-Band plan. Finally, there is one activity using mode JJJ that is wholly contained in the second interval of the S-Band plan. The figure shows the transactions induced by each of these activities on the relevant resources, and the time at which the flaws are detected.

Given an initial activity schedule and S-Band plan, the problems we find include:

1. Changes in the S-Band mode that do not have accompanying swaps.

2. Activities with incorrect modes according to those allowed by the CPS rule set.
3. Activities with modes that are inconsistent with the S-Band plan.
4. Absolute and relative temporal constraint violations.

We do not check for conflicting S-Band modes holding simultaneously, but it is trivial to extend the model to do so.

Due to the existing organization of JSC's Mission Control Center and the architecture of CPS and OSTPV, the prototype application for checking S-Band Packet Swaps is a combination of a Web-based application used by RPEs, a remote client that performs the checks and generates a report for the RPEs, and a report visualization tool (Figure 3). The Web application can be run by RPEs from Mission Control, and allows the RPE to upload a single .zip file containing the CPS rule base, the OSTPV plan, and an XML configuration file. The client consists of a watcher running on a server that continuously scans for new uploads. Once a new upload is detected the files are unpacked. Both the CPS and OSTPV files are XML formatted, so an xslt program is used to extract the elements of the plan and the CPS rules. Certain problems can be caught prior to invocation of EUROPA, e.g. activities with incorrect modes according to those allowed in the CPS rules. All other problems are discovered when EUROPA analyzes the plan. The report is created as an XML formatted document and returned to the invoking Web page.

During the development of the prototype application, we encountered numerous interesting features of the existing tools and plans that are worth mentioning. First, we discovered that the Swap activity rule was not encoded in CPS (although CPS is certainly capable of representing this rule). In addition, there was some question about how long the Swap activity duration should be (information ranged from 5 minutes to 15 minutes). There was some question as to whether the Swap should end the second the mode change was implemented, or the second before the mode change was implemented. On a related note, the first sample plans we analyzed contained missing Swap operations. Finally, some additional CPS fields may be needed to completely identify the set of activities to analyze, but the rules for doing so caused significant complication and were ultimately discarded for the first prototype. As a final observation, we note that while the format of the XML schemas for both CPS and OSTPV are only meant to be machine readable, the selection of the parameter names propagates to the CPS and OSTPV interfaces.

6. Conclusions and Future Work

We have described the challenge of evolving mission operations tools for human spaceflight, specifically in the context of ISS operations. We have shown that, as the complexity of long-term missions increases over time, that mission operations tools must be responsive to changes. We hilight this issue with the case of changing needs for checking S-Band packet swap plans and activity plans on ISS, and have described an initial deep prototype of the long-term solution to this problem.

The fundamental reasons for confusion and lack of tool interoperability include incompatible XML formats, incompatible semantics due to choice of field names and field contents requiring complex translation, one-way data flow (CPS to OSTPV only), incomplete translation of relevant information, and lack of ability to check STPs in OSTPV after modification. These solutions were adequate until the changing needs of mission operations made it possible to change the STP and introduce conflicts. Our current prototype partially addresses many, but not all, of these issues; it is part of a broader effort to understand the need for tool interoperability and enhance JSC's current tool set.

One problem that does not currently arise is temporal constraint violations; these are not frequently present in the STP at this level of abstraction. However, this may be a problem in the future; as noted in [2], some constraints are presently ignored during integration of plans at JSC, and tighter integration of plans may result in this need. The present architecture is well positioned to handle this need; we have demonstrated the ability to check such constraint violations already as part of the regression tests we have run on the prototype.

At present there are 9 S-Band modes; however, this is likely to change as ISS operations continue and ISS construction results in new modules. Not only will the number of modes change, but the labeling scheme may change as well. This type of volatility in the rules is yet another reason for continuing to improve the tool suite; it should be easy to roll with such changes.

In the short term this solution introduces another rulebase in a different rule language to keep consistent with CPS. As noted in as noted in [2], this problem already exists between tools and between organizations using the same tools. This issue will be partially

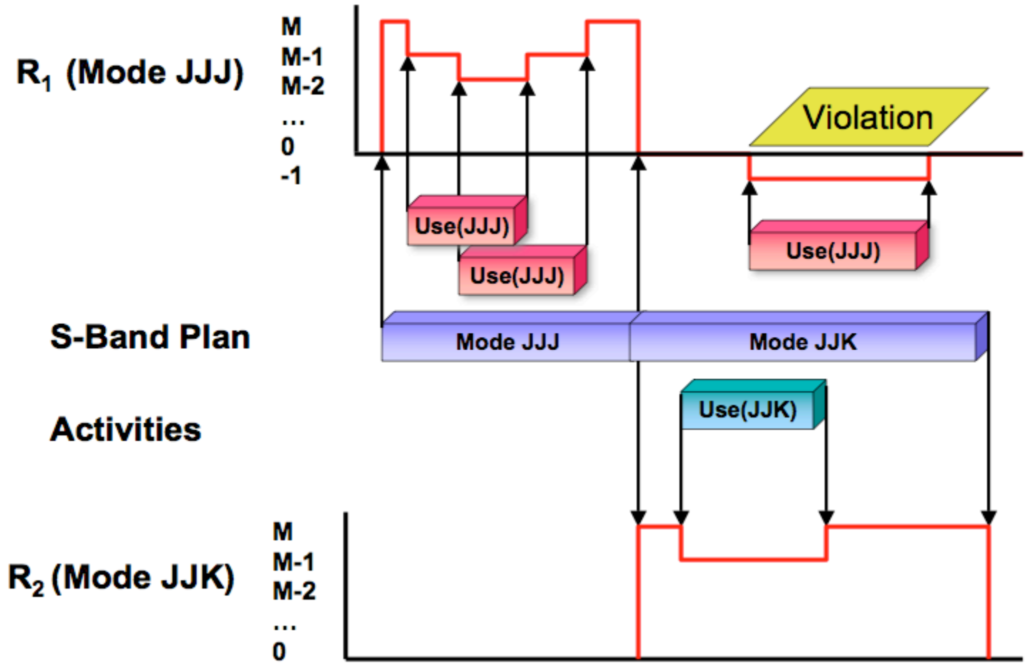

Figure 5. A simple STP showing the S-Band plan, activities using S-Band modes, associated resources, transactions, and one violation.

resolved by the introduction of a new XML format exported by CPS (Cycle 21) that includes all of the rules. In this paper we describe a combination of hand-coded and automated translation of the rules. Thus, JSC and ARC are looking ahead to ensure that rulebases are integrated automatically.

EUROPA contains features like constrained move where the interface will move constrained activities within their allowed temporal bounds as the user moves a target activity. The system will automatically generate a list of violations that exist for various activities and attempt to explain what is causing the violation. The user can manually select "Fix Violations" to have the EUROPA planner attempt to fix all the existing violations in the plan. In this case, EUROPA computes new times for activities or may unscheduled activities that introduce violations that cannot otherwise be repaired. The changes EUROPA introduces can be undone, and each activity that is moved is visually distinguished and displays the change EUROPA has made. In the future we expect these features to enhance OSTPV even further.

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